

PB 161610



Technical Note

No. 109

Boulder Laboratories

A COMPILATION OF THE PHYSICAL EQUILIBRIA AND RELATED PROPERTIES OF THE HYDROGEN-HELIUM SYSTEM

BY

D. E. DRAYER AND T. M. FLYNN



U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

Functions and Activities

The functions of the National Bureau of Standards are set forth in the Act of Congress, March 3, 1901, as amended by Congress in Public Law 619, 1950. These include the development and maintenance of the national standards of measurement and the provision of means and methods for making measurements consistent with these standards; the determination of physical constants and properties of materials; the development of methods and instruments for testing materials, devices, and structures; advisory services to government agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; and the development of standard practices, codes, and specifications. The work includes basic and applied research, development, engineering, instrumentation, testing, evaluation, calibration services, and various consultation and information services. Research projects are also performed for other government agencies when the work relates to and supplements the basic program of the Bureau or when the Bureau's unique competence is required. The scope of activities is suggested by the listing of divisions and sections on the inside of the back cover.

Publications

The results of the Bureau's work take the form of either actual equipment and devices or published papers. These papers appear either in the Bureau's own series of publications or in the journals of professional and scientific societies. The Bureau itself publishes three periodicals available from the Government Printing Office: The Journal of Research, published in four separate sections, presents complete scientific and technical papers; the Technical News Bulletin presents summary and preliminary reports on work in progress; and Basic Radio Propagation Predictions provides data for determining the best frequencies to use for radio communications throughout the world. There are also five series of nonperiodical publications: Monographs, Applied Mathematics Series, Handbooks, Miscellaneous Publications, and Technical Notes.

Information on the Bureau's publications can be found in NBS Circular 460, Publications of the National Bureau of Standards (\$1.25) and its Supplement (\$1.50), available from the Superintendent of Documents, Government Printing Office, Washington 25, D.C.

NATIONAL BUREAU OF STANDARDS

Technical Note

June 1961

A Compilation of the
Physical Equilibria and Related Properties
of the
Hydrogen-Helium
System

by

Dennis E. Drayer

and

Thomas M. Flynn

NBS Technical Notes are designed to supplement the Bureau's regular publications program. They provide a means for making available scientific data that are of transient or limited interest. Technical Notes may be listed or referred to in the open literature. They are for sale by the Office of Technical Services, U. S. Department of Commerce, Washington 25, D. C.

DISTRIBUTED BY

UNITED STATES DEPARTMENT OF COMMERCE

OFFICE OF TECHNICAL SERVICES

WASHINGTON 25, D. C.

Price \$ 1.25

Contents

	Page
List of Tables	iii
List of Figures	iv
Abstract	v
1. Introduction	1
1.1 Purpose	1
1.2 Organization	1
1.3 Scope	1
2. Survey of Literature	2
3. Discussion of Available Data	2
4. K-Factor Charts	4
5. Phenomena Index	9
5.1 Hydrogen	10
5.2 Helium	11
6. Properties Index	12
6.1 Hydrogen	13
6.2 Helium	15
7. Processes Index	17
7.1 Hydrogen	18
7.2 Helium	19
8. Bibliography of References	20
9. Appendix	49

List of Tables

Table		Page
I	Helium-Hydrogen Pressure-Concentration Data	50

List of Figures

Figure		Page
1.	Regions Covered by Published Data	3
2.	Helium-Hydrogen Vapor-Liquid Equilibria Data: Helium K-Factors	5
3.	Helium-Hydrogen Vapor-Liquid Equilibria Data: Hydrogen K-Factors	6
4.	Vapor-Liquid Equilibria Helium-Hydrogen System	7

Abstract

Published data have been used to calculate K-factors for the helium-hydrogen system over the range of 17.4° to 21.8° K and 2 to 32 atmospheres pressure. K-factors are presented graphically for three isotherms over this range. A bibliography of approximately 290 references is also presented on related properties for this system and for the pure components.

1. Introduction

1.1 Purpose

Hydrogen is frequently found as a companion gas in helium sources. If this helium is to be liquefied, a most rigorous purification is required to prevent blocking of the liquefier by solid impurities. The exacting design of such a helium purification system requires a knowledge of the physical equilibria behavior of the hydrogen-helium system.

As an initial step in the study of the physical equilibria of the hydrogen-helium system, a literature survey was made. This paper presents the results of that survey, which includes the current knowledge of the vapor-liquid equilibria, and selected properties of the pure components.

1.2 Organization

The information is presented in three principal parts: (1) physical equilibria with major emphasis on vapor-liquid equilibria; (2) properties related to physical equilibria; and (3) a bibliography of references. Some discussion is presented with Part (1). The information of Part (2) is presented in tabular form showing the reference where important data are to be found. Part (3), the Bibliography, lists the references alphabetically by author.

1.3 Scope

A literature search, as summarized in NBS Technical Note No. 56, revealed most of the pertinent data. Such data were abstracted, and presented in the form of K-factor charts, and as a bibliography of references for related areas of interest. The areas searched are presented in the above reference and will not be enumerated here. Generally speaking, the literature was searched extensively and includes articles published up to 1960. This report does, however, include additional references obtained from a search of Volumes 1 through 5 of the series "Advances in Cryogenic Engineering".

2. Survey of Literature

Only one reference was found relating to the vapor-liquid equilibria for the helium-hydrogen system. This reference, Smith (247), presented pressure-concentration data for three temperatures, 17.4° , 20.4° and 21.8° K.

No related physical data are actually presented in this paper; only the references for such material are listed. Other areas so covered include adsorption phenomena, purification processes, solubility relationships, density and compressibility data, thermodynamic and transport properties, P-V-T data, critical constants, virial coefficients, analytical techniques and various processing references. Such material for the pure components as well as for mixtures of helium and of hydrogen is included in many cases.

The P-T region explored by Smith (247) is shown in Figure 1. (The data needed to prepare the P-T diagrams for hydrogen and helium were taken from Johnson (134), Scott et al. (243) and Keesom (151)).

3. Discussion of Available Data

Admittedly, the data presented herein cover only a narrow temperature range: namely, from 17.4° to 21.8° K. However, for this system one could expect the data, at best, to vary over a narrow range. Complete data would extend roughly from the triple-point temperature of hydrogen (13.9° K) to the critical temperature (33.0° K). The difficulties of investigating this system completely are obvious.

The treatment given the original data of Smith (247) consisted of making appropriate calculations to arrive at K-factors for each component. (In some cases it was necessary to supplement the tabulated data of Smith with P-x and P-y values from his various plots). K is defined as y/x ; where y is the mole fraction of a component in the vapor phase and x is the mole fraction of that component in the liquid phase. K-factors were calculated for each component at a given temperature and pressure. Initially a plot of K versus P (total pressure) was prepared for each component. The data did show some scatter, especially for helium K-factors. The best smooth curve was drawn through the plotted points and this curve was then transferred to another plot (Figure 4).

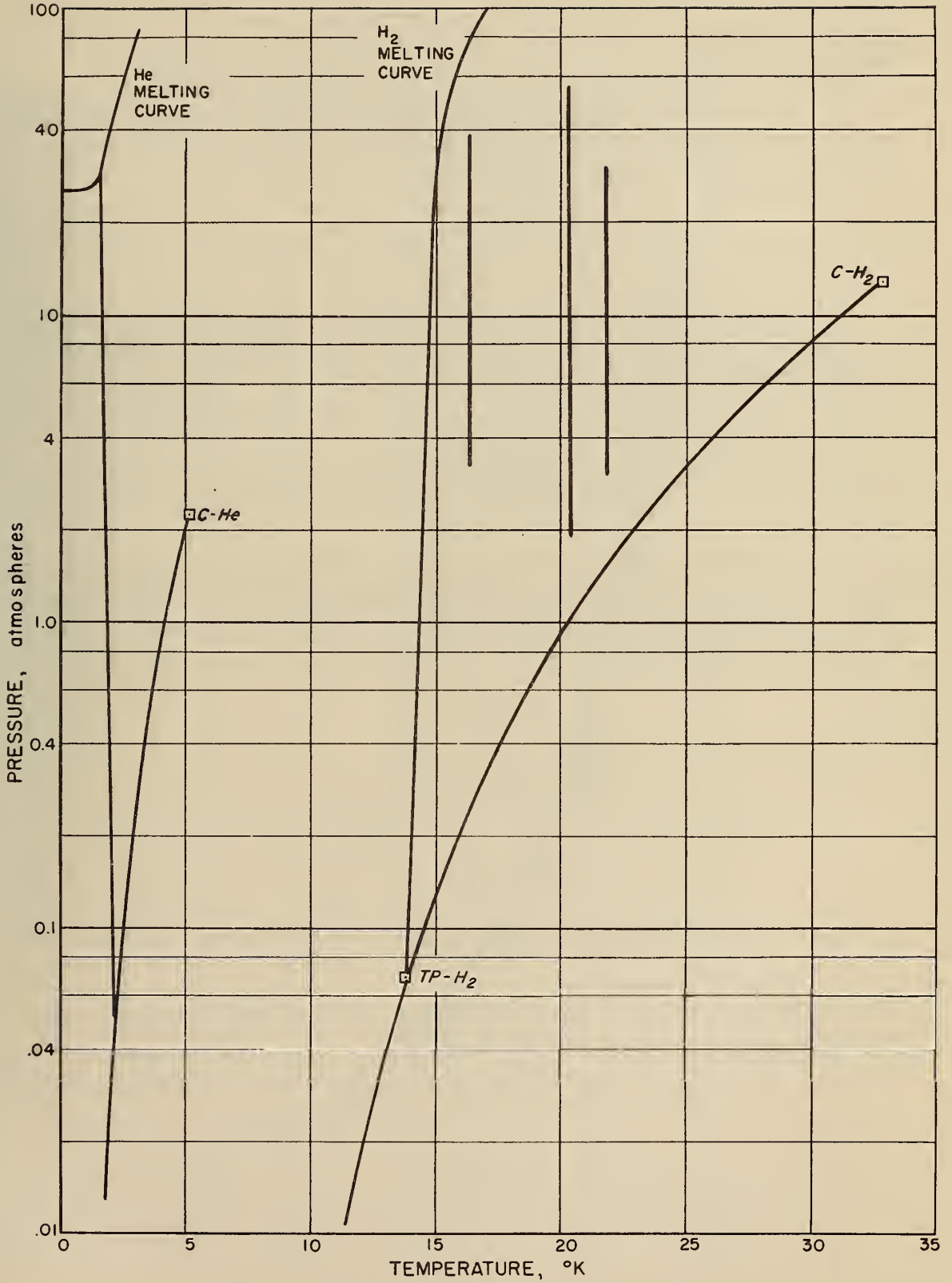


Figure 1. Regions Covered by Published Data

It should be noted that the 20.4° and 21.8° K isotherms for helium cross at approximately 10 atmospheres. Since the Boyle point of helium is near 20° K, one would expect a reversal of the gas solubility in that region. This is in fact shown by the data.

It is not the purpose of this article to make a test of the data for thermodynamic consistency. Smith does treat his data from several thermodynamic viewpoints.

4. K-Factor Charts

Figures 2 and 3 are plots of the K-factors for helium and for hydrogen, respectively. Figure 4 shows the curves for both helium and hydrogen as taken from Figures 2 and 3. In Figure 4, helium K-factors are above the line $K = 1$ and those for hydrogen are below. If the data extended to higher pressures, the isotherm could be expected to close at the high-pressure end. Such closure would occur at the line $K = 1$. This line thus represents the locus of the plait points.

Figure 4 permits the calculation of the vapor and liquid phase equilibrium composition at a given system temperature and pressure. After obtaining the individual K-factors, one simply substitutes into the following series of equations:

$$K_1 = y_1/x_1 \quad (1)$$

$$K_2 = y_2/x_2 \quad (2)$$

$$x_1 + x_2 = 1.0 \quad (3)$$

$$y_1 + y_2 = 1.0 \quad (4)$$

The subscripts refer to the components, helium and hydrogen. As an example, at $T = 20.4^{\circ}$ and $P = 20$ atm.

$$K_{\text{He}} = 37$$

$$K_{\text{H}_2} = 0.094$$

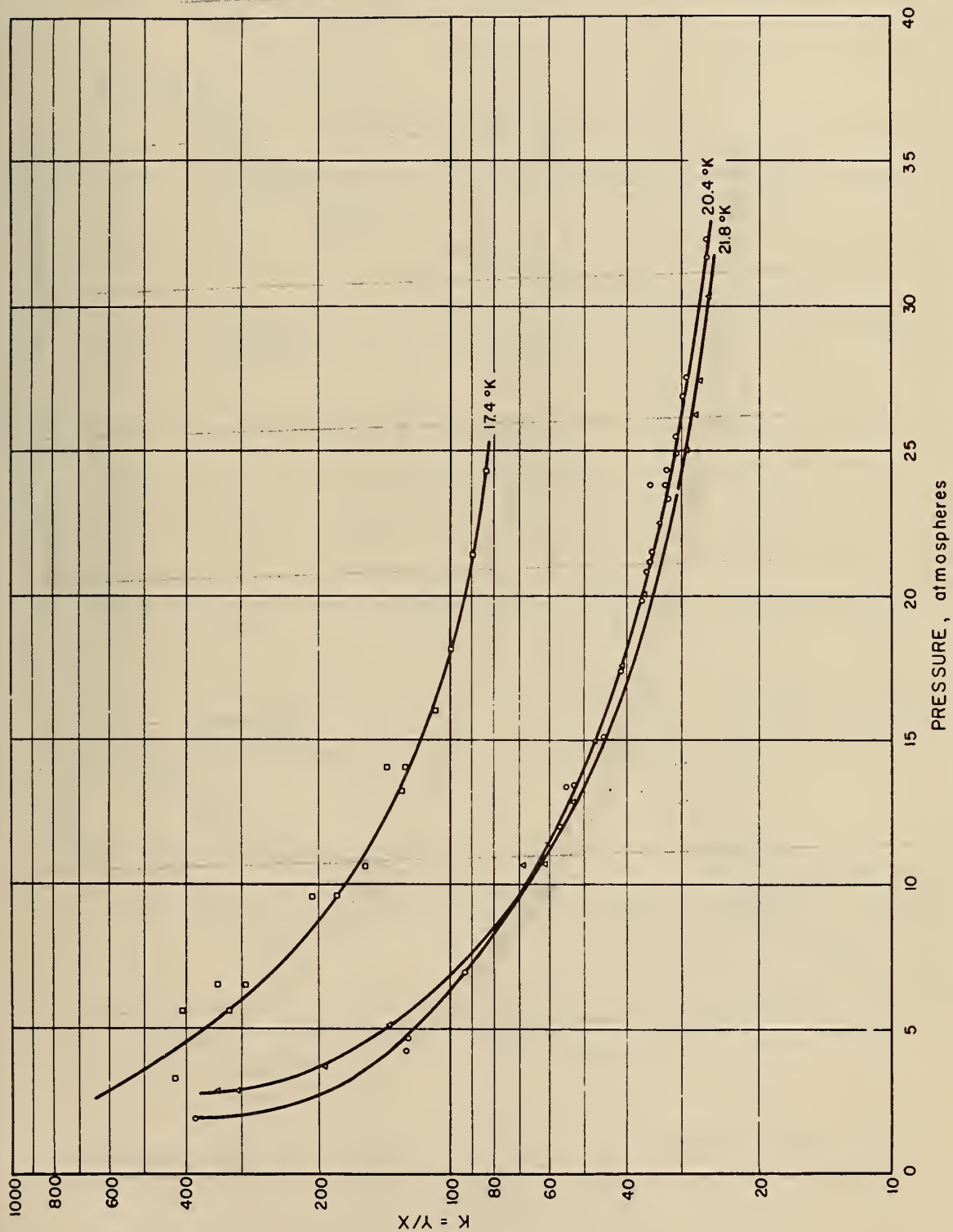


Figure 2. Helium-Hydrogen Vapor-Liquid Equilibria
Data: Helium K-Factors

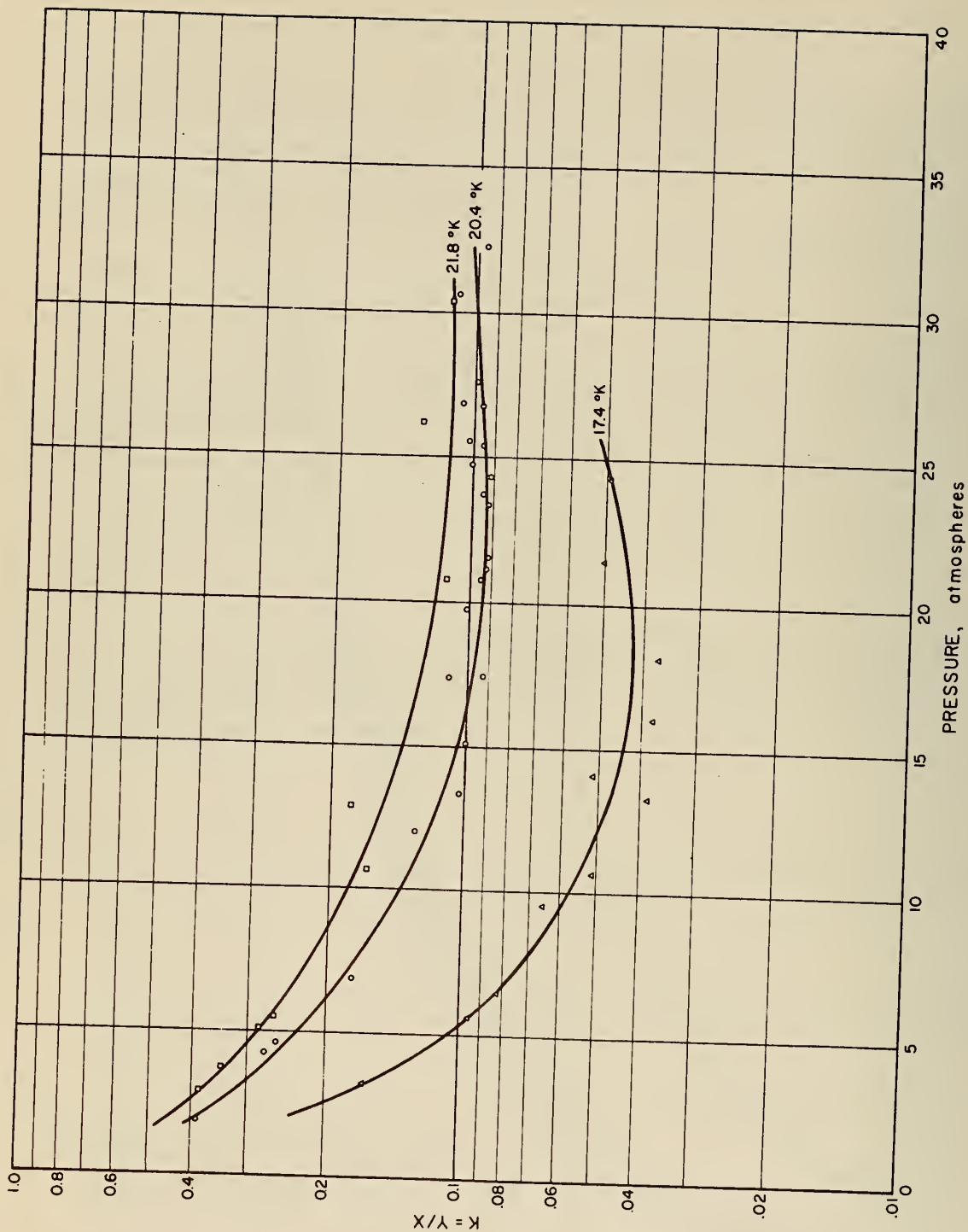


Figure 3. Helium-Hydrogen Vapor-Liquid Equilibria
Data: Hydrogen K-Factors

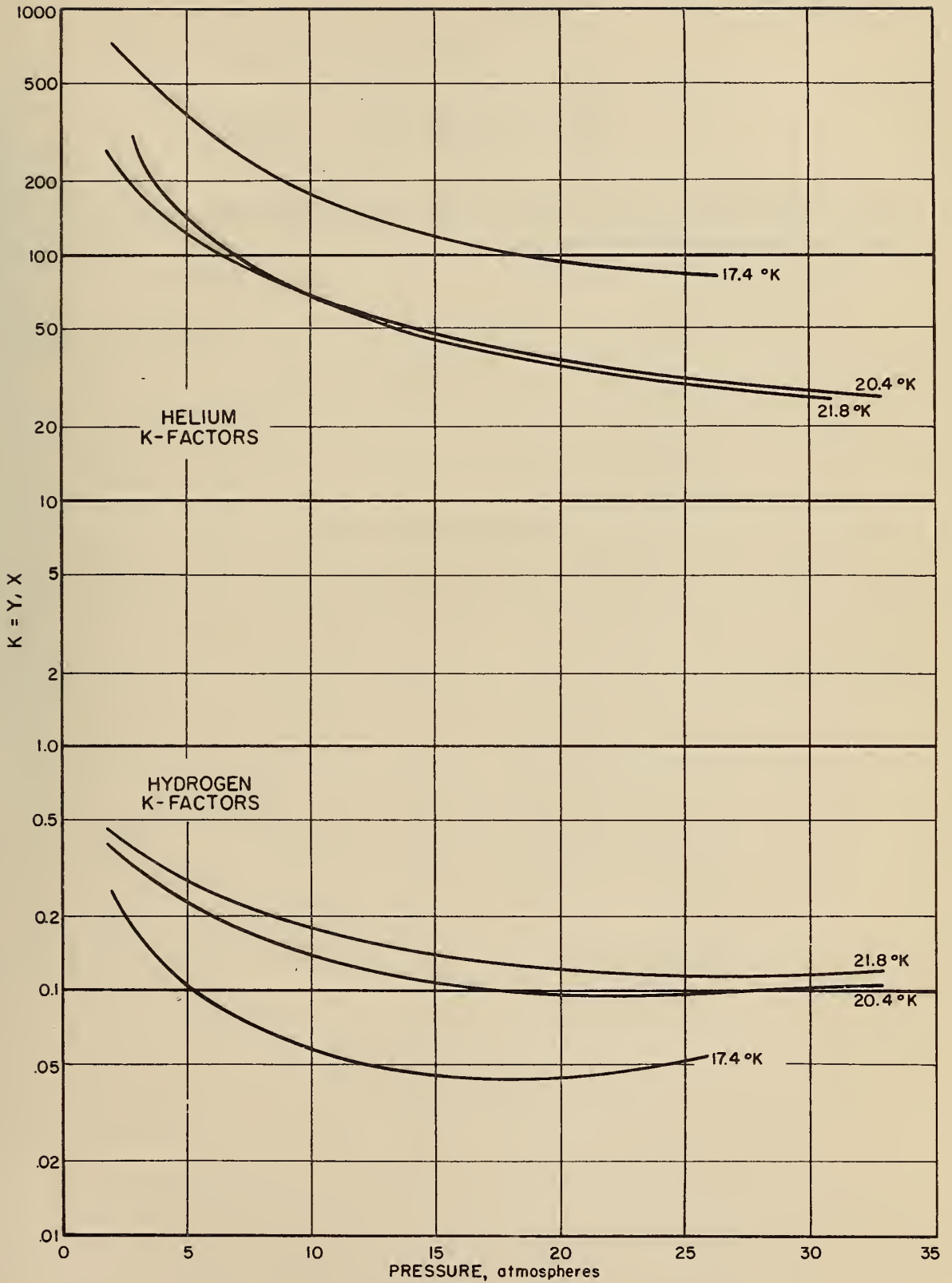


Figure 4. Vapor-Liquid Equilibria Helium-Hydrogen System

Solving equations (1) - (4) gives

$$x_{\text{He}} = 0.0245; \quad x_{\text{H}_2} = 0.9755$$

$$y_{\text{He}} = 0.9083; \quad y_{\text{H}_2} = 0.0917$$

Other relationships involving K-factors, e.g. relative volatilities, could also be easily calculated.

5.0

Phenomena Index

MAJOR COMPONENT

HYDROGEN

Category	Other Components	References
Adsorption		9, 12, 59, 62, 75, 86, 126, 130, 133, 158, 159, 165, 166, 179, 180, 181, 188, 204, 218, 220, 221, 226, 249, 255, 257
	Carbon Dioxide	121
	Nitrogen	135, 257
Phase Equilibria		91, 92, 174, 224
	Butane	203
	Deuterium	170
	Helium	247
	Hydrocarbons	216, 234
	Methane	71
	Nitrogen	96, 217
	Non-Polar Solvents	45
	Paraffins	178
	Water	14
	Water-Nitrogen	14
Purification		56, 57, 64, 122, 141, 149, 268
	Nitrogen	268

Phenomena

MAJOR COMPONENT
HELIUM

Category	Other Components	References
Adsorption		8, 70, 80, 103, 129, 131, 132, 146, 155, 186, 189, 200, 237
	Neon-Nitrogen	269
Phase Equi- libria	Ammonia	254
	Argon	150
	Carbon Dioxide	254
	Hydrogen	247
	Methane	94, 95
	Nitrogen	72, 73, 93, 161
	Propane	253
Purification		24, 44, 175, 260
	Neon	65
	Nitrogen	72

6.0

Properties Index

Properties

MAJOR COMPONENT
HYDROGEN

Category	Other Components	References
Beattie-Bridge- man Constants		17, 54
Critical Constants		10, 21, 68, 84, 124, 134, 173, 225, 261
Density, Compres- sibility, Expansion		2, 3, 6, 11, 13, 15, 16, 21, 31, 55, 60, 68, 99, 109, 110, 134, 139, 145, 167, 173, 185, 190, 191, 193, 225, 231, 235, 242, 263, 271
	Nitrogen	13, 15, 263
Equations of State, Corres- ponding States		1, 17, 19, 42, 54, 83, 184, 240
Isotherms		20, 48, 125, 144, 192, 195, 206, 207, 209, 241, 252, 258
	Carbon Monoxide	241, 252
	Helium	20
	Nitrogen	258
Lennard-Jones Potentials		177
Thermodynamic Properties		25, 26, 53, 55, 66, 68, 74, 85, 88, 89, 107, 119, 128, 134, 136, 138, 152, 169, 171, 194, 225, 243, 246, 248, 265
	Carbon Monoxide	107
	Nitrogen	107

Properties (Continued)

MAJOR COMPONENT

HYDROGEN

Category	Other Components	References
Transport Properties		6, 18, 42, 68, 104, 113, 120, 134, 198, 223, 225, 231, 236
Vapor Pressure		10, 28, 31, 37, 39, 43, 55, 68, 82, 84, 99, 101, 105, 108, 115, 123, 134, 137, 140, 196, 197, 210, 225, 243, 245, 248, 262
	Helium	90
	Nitrogen	82
Virial Coefficients		162, 198, 199, 205, 238, 239
	Carbon Dioxide	47

Properties

MAJOR COMPONENT

HELIUM

Category	Other Components	References
Beattie-Bridge-man Constants		17
Critical Constants		21, 97, 111, 118, 134, 151, 173, 200, 225, 233, 260, 266
Density, Compres-sibility, Expansion		2, 3, 16, 21, 22, 33, 100, 111, 118, 134, 151, 153, 167, 173, 200, 219, 225, 231, 233, 260, 264
	Carbon Dioxide	112
	Carbon Monoxide	187
Equations of State, Corres-ponding States		17, 27, 147, 168, 184, 240, 260
Isotherms		125, 142, 143, 156, 209, 264
	Hydrogen	20
Thermodynamic Properties		4, 22, 23, 63, 111, 134, 151, 152, 171, 186, 200, 225, 231, 260
	Nitrogen	232
Transport Properties		5, 51, 100, 104, 111, 113 118, 120, 134, 151, 200, 225, 231, 260
Vapor Pressure		29, 41, 61, 97, 100, 111, 118, 134, 151, 196, 200, 219, 225, 233, 260
	Hydrogen	90
Virial Coeffi-cients		36, 52, 106, 148, 154, 157, 160, 163, 164, 205

Properties (Continued)

MAJOR COMPONENT

HELIUM

Category	Other Components	References
	Carbon Dioxide	46
	Nitrogen	172

7.0

Processes Index

Processes

MAJOR COMPONENT
HYDROGEN

Category	Other Components	References
Analytical		211
	Carbon Dioxide - Oxygen-Carbon Monoxide	79
	Helium	247
	Methane	114
	Methane-Ethane	202
	Nitrogen-Oxygen- Helium	270
Distillation		56, 57, 76, 244, 251
	Deuterium	77, 78
Equipment		32, 34, 38, 58, 98, 116, 127, 222, 228
Handling		34, 35, 176, 201, 210, 214, 222, 228, 230, 256
Heat Transfer		40, 227, 259
	Helium	267
Manufacture		49, 66, 149, 208, 212, 256
Safety		35, 116

Processes

MAJOR COMPONENT
HELIUM

Category	Other Components	References
Analytical		50, 87, 117, 213
	Hydrogen	247
	Nitrogen-Oxygen-Hydrogen	270
Equipment		29, 67, 98, 102, 183, 215, 250
Handling		30, 182, 214
Heat Transfer		81, 229
	Hydrogen	267
Manufacture		7, 24, 182, 183, 200
	Nitrogen	72

8.0

Bibliography of References

1. van Agt, F. The behavior of hydrogen relative to the law of corresponding states
Commun. Kamerlingh Onnes Lab. Univ. Leiden No. 176c, 7pp. (1925)
2. van Agt, F. and Kamerlingh Onnes, H. Isotherms of monatomic substances and of their binary mixtures. XXI. The compressibility of hydrogen and helium between 90° and 14° K (in Dutch)
Verslag Gewone Vergader. Afd. Natu. Ned. Akad. Wetenschap. 34, 625-37 (1925)
3. van Agt, F. and Kamerlingh Onnes, H. The Compressibility of hydrogen and helium between 90° and 14° K
Commun. Kamerlingh Onnes Lab. Univ. Leiden No. 176b, 15pp. (1925)
4. Akin, S. W. The thermodynamic properties of helium
Trans. Am. Soc. Mech. Engrs. 72, 751-7 (1954)
5. Amdur, I. Low-temperature transport properties of gases: helium
J. Chem. Phys. 15, 482-7 (1947)
6. Anon. Hydrogen processing; hydrogen reference data
Petrol. Processing 11, 136-8 (1956)
7. Anon. New helium process
Chem. Eng. Progr. 54, No. 6, 106, 110 (1958)
8. Antropoff, A. V., Propfe, H. A., Weil, K., Kalthoff, F., Schmits, L. and Cronenthal, G. R. Investigations of Adsorption of gases from very small to very high pressures. III. Adsorption isotherms of the noble gases and of nitrogen at pressures below atmospheric (in German)
Kolloid-Z. 129, 1-10 (1952)
9. Armbruster, M. H. and Austin, J. E. The adsorption of gases on smooth surfaces of steel: argon, neon, hydrogen, nitrogen, carbon monoxide and carbon dioxide
J. Am. Chem. Soc. 66, 159-71 (1944)

10. Arnold, R. D. and Hoge, H. J. A test of the ideal solution laws for hydrogen, hydrogen deuteride and deuterium. Vapor pressures and critical constants of the individual components J. Chem. Phys. 18, 1295 (1950)
11. Augustin, H. Density of liquid hydrogen, index of refraction and dispersion of liquid hydrogen in liquid nitrogen (in German) Ann. Physik [4] , 46, 419-45 (1915)
12. Barrer, R. M. Interaction of hydrogen with micro-crystalline charcoal. II. Activated sorption of hydrogen and methane by carbon Proc. Roy. Soc. (London) A149, 231-69 (1935)
13. Bartlett, E. P. Compressibility isotherms of hydrogen, nitrogen and mixtures of these gases at 0° and pressures to 1000 atmospheres J. Am. Chem. Soc. 49, 687-701 (1927)
14. Bartlett, E. P. The concentration of water vapor in compressed hydrogen, nitrogen and a mixture of these gases in the presence of condensed water J. Am. Chem. Soc. 49, 65-78 (1927)
15. Bartlett, E. P., Cupples, H. L. and Tremearne, T. H. Compressibility isotherms of hydrogen, nitrogen and a 3:1 mixture of these gases at temperatures between 0° and 400° and at pressures to 1000 atmospheres J. Am. Chem. Soc. 50, 1275-88 (1928)
16. Beattie, J. A. and Bridgeman, O. C. A new equation of state for fluids. II. Application to helium, neon, hydrogen, nitrogen, oxygen, air and methane. III. The normal densities and compressibilities of several gases at 0°C J. Am. Chem. Soc. 50, 3133-8 (1928)
17. Beattie, J. A. and Ikehara, S. An equation of state for gas mixtures. II. A study of the methods of combination of the constants of the Beattie-Bridgeman equation of state Proc. Am. Acad. Arts Sci. 64, 127-76 (1930)
18. Becker, E. W. and Stehl, O. The viscosity difference between ortho and para hydrogen at low temperatures (in German) Z. Physik 133, 615-28 (1952)

19. Beenakker, J. J. M. and Varekamp, F. H. Equation of state of hydrogen and its isotopes below 20°K
Bull. inst. intern. froid Annexe 1956, No. 2, 189-94 (1956)
20. Beenakker, J. J. M., Varekamp, F. H. and van Itterbeek, A. The isotherms of hydrogen isotopes and their mixtures with helium at the boiling point of nitrogen
Physica 25, 9-24 (1959)
21. Benson, S. W. Critical densities and related properties of liquids
J. Phys. & Colloid Chem. 52, 1060-74 (1948)
22. Berman, R. and Poulter, J. On the latent heat and vapor density of helium
Phil. Mag. [7], 43, 1047-54 (1952)
23. Bhagat, S. D. Specific heat and entropy of liquid helium 3
Proc. Phys. Soc. (London) 69B, 1117-22 (1956)
24. Biondi, M. A. Preparation of extremely pure helium gas
Rev. Sci. Instr. 22, 535-6 (1951)
25. Bjerrum, N. The specific heat of gases. II. Oxygen, hydrogen, argon, nitrogen and water vapor (in German)
Z. Elektrochem. 18, 101-4 (1912)
26. Bol'shakov, P. E., Gamburg, D. Yu., Efremova, G. D., Khazanova, N. E. and Tsiklis, D. S. Entropy-temperature diagrams for hydrogen, nitrogen, carbon monoxide, ethane and ethylene (in Russian)
Trudy Gosudarst. Nauch.-Issledovatel. i Proekt. Inst. Azot. Prom. 1952, No. 1, 67-71
27. Borelius, G. Equations of state for liquid helium (in German)
Arkiv Fysik 13, 369-78 (1958)
28. Borovik-Romanov, A. S. and Strelkov, P. G. New type of gas thermometer and determination of the boiling temperature of hydrogen (in Russian)
Doklady Akad. Nauk S.S.S.R. 83, 59-61 (1952)

29. Brickwedde, F. J., van Dijk, H., Durieux, M., Clement, J. R. and Logan, J. K. He^4 scale of temperatures
J. Research Natl. Bur. Standards 64A, 1-17 (1960)
30. Brown, R. E. Economic and other aspects of the distribution of Navy helium in liquid form
Advances in Cryogenic Eng. 3, 114-24 (1960)
31. Brunot, A. W. Properties of hydrogen mixtures
Trans. Am. Soc. Mech. Engrs. 62, 613-9 (1940)
32. Burgeson, D. A. Results of flowmeter calibration in liquid hydrogen
Advances in Cryogenic Eng. 5, 307 (1960)
33. Burt, F. P. Compressibilities of helium and neon
Trans. Faraday Soc. 6, 19-26 (1910)
34. Caine, G., Schafer, L. and Burgeson, D. A. Pumping of liquid hydrogen
Advances in Cryogenic Eng. 4, 241-54 (1960)
35. Cassutt, L. H., Maddocks, F. E. and Sawyer, W. A. A study of the hazards in the storage and handling of liquid hydrogen
Advances in Cryogenic Eng. 5, 55-61 (1960)
36. Cath, P. G. and Kamerlingh Onnes, H. Measurement of very low temperatures. XXX. Comparison of the helium, argon, neon, oxygen and nitrogen thermometers with hydrogen thermometer corrections which will reduce the indications of these thermometers to the international scale of Kelvin. The second coefficient of the virial for helium, argon, neon, oxygen and nitrogen below 0° (in French)
Arch. neerl. sci. 6, 1-30 (1922)
37. Cath, P. G. and Kamerlingh Onnes, H. The measurement of low temperatures. XXVII. Vapor pressure of hydrogen in the neighborhood of the boiling point and between the boiling point and the critical point
Commun. Kamerlingh Onnes Lab. Univ. Leiden No. 152a, 15pp. (1917)

38. Chelton, D. B., Mann, D. B. and Byrns, R. A. A large liquid hydrogen bubble chamber
Advances in Cryogenic Eng. 2, 325-9 (1960)
39. Chester, F. P. and Dugdale, J. S. Melting curves of deuterium and hydrogen
Phys. Rev. 95, 278-9 (1954)
40. Class, C. R., DeHaan, J. R., Piccone, M. and Cost, R. B. Boiling heat transfer to liquid hydrogen from flat surfaces
Advances in Cryogenic Eng. 5, 254-61 (1960)
41. Clement, J. R., Logan, J. K. and Gaffney, J. Liquid helium vapor pressure equation
Phys. Rev. 100, 743-4 (1955)
42. Cohen, E. D. G., Offerhaus, J. M., van Leeuwen, J. M. J., Roos, B. W. and DeBoer, J. The transport properties and equation of state of gaseous para- and ortho-hydrogen and their mixture below 40° K
Physica 21, 737-9 (1955)
43. Cohen, K. and Urey, H. C. Van der Waals' forces and the vapor pressures of ortho and para hydrogen and ortho and para deuterium
J. Chem. Phys. 7, 157-63 (1939)
44. Cook, J. W. Purification of helium
Phys. Rev. 29, 920 (1927)
45. Cook, M. W., Hanson, D. N. and Alder, B. J. Solubility of hydrogen and deuterium in non-polar solvents
J. Chem. Phys. 26, 748-51 (1957)
46. Cottrell, T. L. and Hamilton, R. A. Second virial coefficients of gases and mixtures. I. Carbon dioxide and helium mixtures
Trans. Faraday Soc. 52, 156-60 (1956)
47. Cottrell, T. L., Hamilton, R. A. and Taubinger, R. P. Second virial coefficients of gases and mixtures. II. Mixtures of carbon dioxide with nitrogen, oxygen, carbon monoxide, argon and hydrogen
Trans. Faraday Soc. 52, 1310-2 (1956)

48. Crommelin, C. A. and Swallow, J. C. Isotherms of hydrogen from -217° to -240° at pressures up to 60 atmospheres Commun. Kamerlingh Onnes Lab. Univ. Leiden No. 172a, 7pp. (1924)
49. Cronan, C. S. Small volume pure hydrogen at bulk cost Chem. Eng. 66, No. 16, 60-2 (1959)
50. Davis, C. E., Hunt, R. H. and O'Neal, M. J. Determination of helium in the parts-per-million range Anal. Chem. 29, 1720 (1957)
51. De Boer, J. and Cohen, E. D. G. Viscosity of gaseous helium at low temperatures Physica 17, 993-1000 (1951)
52. De Boer, J. and Michels, A. Quantum-mechanical calculations of the second virial coefficient of helium at low temperatures Physica 6, 409-20 (1939)
53. Deming, W. E. and Deming, L. S. Some physical properties of compressed gases. IV. The entropies of nitrogen, carbon monoxide and hydrogen Phys. Rev. 45, 109-13 (1934)
54. Deming, W. E. and Shupe, L. E. Constants of the Beattie-Bridgeman equation of state with Bartlett's p-v-t data on hydrogen J. Am. Chem. Soc. 53, 843-9 (1931)
55. Deming, W. E. and Shupe, L. E. Some physical properties of gases. III. Hydrogen, also nitrogen and carbon monoxide Phys. Rev. 40, 848-59 (1932)
56. Denton, W. H., Shaw, B., Gayler, R. and Seager, P. Purification of hydrogen for distillation. Part II Trans. Inst. Chem. Engrs. (London) 37, 276-88 (1959)
57. Denton, W. H., Shaw, B. and Ward, D. E. Purification of hydrogen for distillation Trans. Inst. Chem. Engrs. (London) 36, 179-200 (1958)

58. DeSorbo, W., Milton, R. M. and Andrews, D. H. New cryogenic methods of using liquid hydrogen
Chem. Revs. 39, 403-17 (1946)
59. Dewar, J. The adsorption and thermal evolution of gases occluded in charcoal at low temperatures. Adsorption of hydrogen, nitrogen, oxygen, argon, helium, electrolytic gas, carbonic oxide and oxygen and carbonic oxide at 0°C
Proc. Roy. Soc. (London) A74, 122-7 (1904)
60. Dewar, J. The densities of solid oxygen, nitrogen, hydrogen, argon, carbon monoxide, etc.
Proc. Roy. Soc. (London) A73, 151-61 (1904)
61. van Dijk, H. and Shoenberg, D. Tables of vapor pressure of liquid helium
Nature 164, 151 (1949)
62. van Dingenen, W. and van Itterbeek, A. Measurements of the adsorption of light and heavy hydrogen on charcoal between 90° and 17°K
Physica 6, 49-58 (1939)
63. Dugdale, J. S. and Simon, F. E. Thermodynamic properties of melting and solid helium
Proc. Roy. Soc. (London) A218, 291-310 (1953)
64. English, W. N. Continuous purification of hydrogen in a large electron pulse chamber
Rev. Sci. Instr. 22, 598-600 (1951)
65. Ermolin, M. G. Method of quantitative separation of helium-neon mixture (in Russian)
Trudy Radietvogo Inst. im. V. G. Khlopina 6, 119-38 (1957)
66. Eyre, D. V. Hydrogen separation: a compromise with reversibility
Advances in Cryogenic Eng. 4, 319-25 (1960)
67. Fairbank, W. M., Blevins, M. E., Block, M. M., Buckingham, M. J., Harth, E. M., Leitner, J. and Slaughter, G. G. Liquid helium bubble chamber
Advances in Cryogenic Eng. 2, 330-5 (1960)

68. Falk, G. and Mann, A. Viscosity of o- and p-hydrogen (in German)
Z. Physik 142, 277-96 (1955)
69. Farkas, A. Orthohydrogen, parahydrogen and heavy hydrogen
University Press, Cambridge, 215pp. (1935)
70. Fastovskii, V. G. and Girskaia, L. A. Adsorption of neon and helium (in Russian)
Zhur. Khim. Prom. 14, 358-61 (1937)
71. Fastovskii, V. G. and Gonikberg, M. G. Solubility of gases in liquids at low temperatures and high pressure. III. Solubility of hydrogen in liquid methane (in Russian)
Acta Physicochim. U.R.S.S. 12, 427-8 (1940)
72. Fedoritenko, A. and Ruhemann, M. Physical bases for separation of helium and nitrogen (in Russian)
Zhur. Tekh. Fiz. 7, 35-42 (1937)
73. Fedoritenko, A. and Ruhemann, M. Equilibrium diagram of helium-nitrogen mixtures
Tech. Phys. U.S.S.R. 4, 36-43 (1937)
74. Fenning, R. W. and Whiffin, A. C. The specific heat of gases at high temperatures: carbon monoxide, nitrogen, carbon dioxide, hydrogen and water vapor. Explosion method
Trans. Roy. Soc. (London) A238, 149-212 (1939)
75. Firth, J. B. Sorption of hydrogen by palladium at low temperatures
J. Chem. Soc. 117, 171-83 (1920)
76. Flynn, T. M. Pilot plant data for hydrogen isotope distillation
Chem. Eng. Progr. 56, No. 3, 37-42 (1960)
77. Flynn, T. M., Weitzel, D. H., Timmerhaus, K. D., Vander Arend, P. C. and Draper, J. W. Distillation of hydrogen-deuterium mixtures
Advances in Cryogenic Eng. 2, 39-45 (1960)
78. Flynn, T. M., Timmerhaus, K. D. and Weitzel, D. H. Pilot plant studies of the low temperature distillation of hydrogen isotopes
Advances in Cryogenic Eng. 4, 464-75 (1960)

79. Foreman, J. K. Microdetermination of carbon dioxide, oxygen, carbon monoxide and hydrogen in gaseous mixtures (in Austrian) *Mikrochim. Acta* 1956, 1481-7 (1956)
80. Frederikse, H. P. R. and Corter, C. J. Investigations on the adsorption of helium at very low temperatures
Physica 16, 402-18 (1950)
81. Frederking, T. H. K. Film boiling of helium I and other liquefied gases on single wires
A.I.Ch.E. Journal 5, 403-6 (1959)
82. Friedman, A. S. P-V-T relationships of gaseous hydrogen, nitrogen and hydrogen-nitrogen mixtures
Ph.D. Thesis, Ohio State Univ., Columbus (1950)
83. Friedman, A. S. and Oppenheim, I. Equation of state of hydrogen isotopes at intermediate densities
Phys. Rev. 98, 258 (1955)
84. Friedman, A. S., White, D. and Johnston, H. L. Critical constants, boiling points, triple point constants and vapor pressure of the six isotropic hydrogen molecules based on a simple mass relationship
J. Chem. Phys. 19, 126-7 (1951)
85. Friedman, H. L. Nonideality of liquid ortho-para hydrogen solutions
J. Chem. Phys. 27, 220-3 (1957)
86. Frolich, P. K. and White, A. Adsorption of methane and hydrogen on charcoal at high pressure
Ind. Eng. Chem. 22, 1058-60 (1930)
87. Germann, F. E. E., Gagos, K. A. and Neilson, C. A. Apparatus for determination of helium in gases
Ind. Eng. Chem. Anal. Ed. 6, 215-7 (1934)
88. Giacomini, F. A. The temperature dependency of the molecular heats of gases, especially of ammonia, methane and hydrogen, at low temperatures
Phil. Mag. [6], 50, 146-56 (1925)

89. Giauque, W. F. The entropy of hydrogen and the third law of thermodynamics
J. Am. Chem. Soc. 52, 4816-31 (1930)
90. Gibby, C. W., Tanner, C. C. and Masson, I. The pressure of gaseous mixtures. II. Helium and hydrogen and their inter-molecular forces
Proc. Roy. Soc. (London) A122, 283-304 (1929)
91. Gonikberg, M. G. Regular solutions of gases in liquids. I. Regular solutions of hydrogen (in Russian)
Zhur. Fiz. Khim. 14, 582-8 (1940)
92. Gonikberg, M. G. Regular solutions of gases in liquids. II. More concentrated solutions of hydrogen at high pressures (in Russian)
Acta Physicochim. U.R.S.S. 12, 921-30 (1940)
93. Gonikberg, M. G. and Fastovskii, V. G. Solubility of gases in liquids at low temperatures and high pressures. II. Solubility of helium in liquid nitrogen at temperatures from 78.0° to 109.0° K and at pressures up to 295 atmospheres (in Russian)
Acta Physicochim. U.R.S.S. 12, 67-72 (1940)
94. Gonikberg, M. G. and Fastovskii, V. G. Solubility of gases in liquids at low temperatures and high pressures. IV. Solubility of helium in liquid methane at 90.3° and 106.0° K and at pressures up to 160 atmospheres (in Russian)
Acta Physicochim. U.R.S.S. 13, 399-404 (1940)
95. Gonikberg, M. G. and Fastovskii, V. G. The solubility of gases in liquids at low temperatures and high pressures. IV. The solubility of helium in liquid methane at temperatures of 90.3° K and 106° K and pressures up to 160 atmospheres
Foreign Petrol. Technol. 9, 214-9 (1941)
96. Gonikberg, M. G., Fastovskii, V. G. and Gurvitsch, J. G. Solubility of gases in liquids at low temperatures and high pressures. I. Solubility of hydrogen in liquid nitrogen at 79° - 109° K and at pressures up to 190 atmospheres (in Russian)
Acta Physicochim. U.R.S.S. 11, 865-82 (1939)

97. Gopal, R. Correspondence in some solid inorganic substances at their melting and boiling points. IV. Frozen inert gases (in German)
Z. anorg. u. allgem. Chem. 281, 217-20 (1955)
98. Gottzman, C. F. High-pressure liquid hydrogen and helium pumps
Advances in Cryogenic Eng. 5, 289-98 (1960)
99. Granet, I. Physical properties of hydrogen in convenient graphical form
Petrol. Refiner 33, 205-6 (1954)
100. Grassmann, P. Properties of liquid and solid helium (in German)
Naturforscher 102, 61-87 (1957)
101. Gratch, S. Vapor pressure, specific volume, p-v-t data for hydrogen, nitrogen, oxygen, carbon monoxide, carbon dioxide, air, helium, argon and mercury
Trans. Am. Soc. Mech. Engrs. 70, 631-40 (1948)
102. Gray, V. H. and Gelder, T. F. Externally bonded and sealed insulation for liquid hydrogen-fueled rocket tanks
Advances in Cryogenic Eng. 5, 131-8 (1960)
103. Greyson, J. and Aston, J. G. The heats of adsorption of helium and neon on graphitized carbon black
J. Phys. Chem. 61, 610-3 (1957)
104. Grilly, E. R. Relationships between transport properties of gases
Am. J. Phys. 20, 447-50 (1952)
105. Grilly, E. R. The vapor pressures of hydrogen, deuterium and tritium
J. Am. Chem. Soc. 43, 843-6 (1951)
106. Gropper, L. Calculation of the second virial coefficient of helium gas for the lowest measured temperature
Phys. Rev. 55, 1095-7 (1939)

107. Guelperine, N. I. and Naiditch, I. M. "I-S" diagrams for hydrogen, carbon monoxide, nitrogen, nitrogen and hydrogen, and carbon monoxide and hydrogen (in French)
Chim. & ind. (Paris) 34, 1011-20 (1935)
108. van Gulik, W. and Keesom, W. H. The fusion line of hydrogen up to 245 kg/sq cm
Commun. Kamerlingh Onnes Lab. Univ. Leiden No. 192b, 3pp. (1928)
109. Guye, P. A. and Batuecas, T. The compressibility of several gases at 0° and up to one atmosphere, and the deviation from Avogadro's law. I. Oxygen, hydrogen and carbon dioxide (in French)
Helv. Chim. Acta 5, 532-43 (1922)
110. Habada, M. and Hajda, J. Compressibility of hydrogen (in Czech.)
Chem. průmysl 3, 68-72 (1953)
111. Ham, N. S. The properties of liquid helium
Roy. Australian Chem. Inst. J. & Proc. 17, 272-83 (1950)
112. Harper, R. C., Jr. and Miller, J. G. Compressibility of gases. II. Mixtures of carbon dioxide and helium at 30°
J. Chem. Phys. 27, 36-9 (1957)
113. Hawkins, G. A. Brief review of available data on the dynamic viscosity and thermal conductivity for twelve gases
Trans. Am. Soc. Mech. Engrs. 70, 655-9 (1948)
114. Hempel, W. Determination of hydrogen and methane in gas mixtures (in German)
Z. angew. Chem. 25, 1841-5 (1912)
115. Henning, F. and Heuse, W. A new determination of the normal boiling points of oxygen, nitrogen and hydrogen (in German)
Z. Physik 23, 105-16 (1924)
116. Hernandez, H. P. Designing for safety in hydrogen bubble chambers
Advances in Cryogenic Eng. 2, 336-50 (1960)

117. Heuse, W. Gas-thermometric investigations of helium, neon, nitrogen and oxygen (in German)
Z. Physik 37, 157-64 (1926)
118. Hewlett, C. W. Physical properties of liquid helium
Gen. Elec. Rev. 49, 42-7 (1946)
119. Hill, R. W. and Ricketson, B. W. A. A lambda-anomaly in the specific heat of solid hydrogen
Phil. Mag [7], 45, 277-82 (1954)
120. Hirschfelder, J. O., Bird, R. B. and Spotz, E. L. The transport properties of non-polar gases
J. Chem. Phys. 16, 968-81 (1948)
121. Hitz, K. Scheller, W. and Treadwell, W. D. The mixed adsorption of hydrogen, oxygen and nitrogen with carbon dioxide on linden charcoal (in German)
Helv. Chim. Acta 34, 1783-90 (1951)
122. Hofsass, M. Separation of chemically pure hydrogen from gaseous mixtures (in German)
Z. Kompr. flüss. Gase 30, 13-4 (1933)
123. Hoge, H. J. and Arnold, R. D. Vapor pressures of hydrogen, deuterium and hydrogen deuteride and the dew point pressures of their mixtures
J. Research Natl. Bur. Standards 47, 63-74 (1951)
124. Hoge, H. J. and Lassiter, J. W. Critical temperatures, pressures and volumes of hydrogen, deuterium and hydrogen deuteride
J. Research Natl. Bur. Standards 47, 75-9 (1951)
125. Hoborn, L. and Otto, J. Isotherms of helium, hydrogen and neon below -200° (in German)
Z. Physik 38, 359-67 (1926)
126. Hollings, H. and Griffith, R. H. Activated adsorption of hydrogen
Nature 129, 834 (1932)

127. Isakson, V. E., Holben, C. D. and Fogelberg, C. V. Beech aircraft 6000 liter liquid hydrogen dewar
Advances in Cryogenic Eng. 3, 232-7 (1960)
128. van Itterbeek, A. The dependency of C_p/C_v on pressure for hydrogen gas deduced from measurements of the velocity of sound at liquid hydrogen temperatures
Commun. Kamerlingh Onnes Lab. Univ. Leiden, Supp. No. 70b, 7-12 (1932)
129. van Itterbeek, A. and van Dingenen, W. Adsorption isotherms and heats of adsorption of helium on charcoal between 20° and 6°K. New desorption experiments
Physica 5, 529-40 (1938)
130. van Itterbeek, A. and van Dingenen, W. Determination of adsorption isotherms of hydrogen on charcoal between 90° and 50°K in connection with desorption experiments
Physica 4, 389-402 (1937)
131. van Itterbeek, A., van Dingenen, W. and Borghs, J. Adsorption of helium gas on active charcoal between 4.2° and 1.78°K
Nature 144, 249 (1939)
132. van Itterbeek, A., van Dingenen, W. and Borghs, J. Measurements of the adsorption of helium gas on active charcoal between 4.22° and 1.78°K
Physica 6, 951-60 (1939)
133. Johnson, M. C. An analysis of hydrogen adsorption phenomena
Trans. Faraday Soc. 29, 1139-55 (1933)
134. Johnson, V. J. (Editor) A compendium of the properties of materials at low temperatures. Phase I
Natl. Bur. Standards Cryogenic Eng. Lab., Boulder, Colorado (Dec. 1959)
135. Johnson, V. J. Removal of nitrogen from hydrogen with silica gel at low temperatures
Advances in Cryogenic Eng. 3, 11-8 (1960)

136. Johnston, H. L., Bezman, I. I. and Hood, C. B. Joule-Thomson effects in hydrogen at liquid air and at room temperatures
J. Am. Chem. Soc. 68, 2367-73 (1946)
137. Johnston, H. L., Bezman, I. I., Rubin, T., Jensen, L., White, D. and Friedman, A. S. Gaseous data of state for hydrogen between 1 and 200 atmospheres from 20° to 300°K
Phys. Rev. 79, 235 (1950)
138. Johnston, H. L., Clarke, J. T., Rifkin, E. B. and Kerr, E. C. Condensed gas calorimetry. I. Heat capacity, latent heats and entropies of pure para-hydrogen from 12.7° to 20.3°K
J. Am. Chem. Soc. 72, 3933-8 (1950)
139. Johnston, H. L., Keller, W. E. and Friedman, A. S. The compressibility of liquid normal hydrogen from the boiling point to the critical point at pressures up to 100 atmospheres
J. Am. Chem. Soc. 76, 1482-6 (1954)
140. Johnston, H. L. and White, D. Pressure-volume-temperature relationships of gaseous normal hydrogen from its boiling point to room temperature from 0-200 atmospheres
Trans. Am. Soc. Mech. Engrs. 72, 785-7 (1950)
141. Kamerlingh Onnes, H. An apparatus for the purification of gaseous hydrogen by liquid hydrogen (in Dutch)
Koninkl. Akad. Wetenschap. Amsterdam 11, 883-6 (1910)
142. Kamerlingh Onnes, H. Isotherms of helium at -253°C and -259°C
Proc. Acad. Sci. Amsterdam 10, 741-20 (1908)
143. Kamerlingh Onnes, H. Isotherms of helium, 100°C to -217°C
Proc. Acad. Sci. Amsterdam 10, 445-50 (1908)
144. Kamerlingh Onnes, H. and Braak, C. Isotherms of hydrogen between -104°C and 217°C
Commun. Kamerlingh Onnes Lab. Univ. Leiden No. 97a, 28pp. (1906) and Nos. 99a, 3pp. 100a, 9 (1907)

145. Kamerlingh Onnes, H. and Crommelin, C. A. Isotherms of diatomic substances and their binary mixtures. XIII. Liquid densities of hydrogen between the boiling point and the triple points; contraction of hydrogen on freezing
Commun. Kamerlingh Onnes Lab. Univ. Leiden No. 137a, 3pp. (1913)
146. Kanda, E. The adsorption of helium on charcoal below 78°K and thermometry of low temperatures
Bull. Chem. Soc. Japan 13, 241-6 (1938)
147. Kane, G. Equation of state of solid helium
J. Chem. Phys. 9, 568-70 (1941)
148. Kaneka, S. and Kihara, T. Second virial coefficient of helium from the square-well potential
J. Phys. Soc. Japan 11, 471-3 (1956)
149. Kanolt, C. W. and Cook, J. W. Production of pure hydrogen for liquefaction
Ind. Eng. Chem. 17, 183-9 (1925)
150. Karasz, F. E. and Halsey, G. D., Jr. Solubility of helium and neon in liquid argon. An approximation to the entropy of lattice vacancy formation in liquid argon
J. Chem. Phys. 29, 173-9 (1958)
151. Keesom, W. H. Helium
Elsevier Publishing Co., Amsterdam, 494pp. (1946)
152. Keesom, W. H. Thermodynamic investigations including triple point and critical magnitudes of oxygen, argon, nitrogen, neon, hydrogen and helium (in German)
Onnes-Festschrift 1922, 89-163 (1922)
153. Keesom, W. H. and Kraak, H. H. The compressibility of helium gas between 2.6° and 4.2°K
Commun. Kamerlingh Onnes Lab. Univ. Leiden No. 234e, 8pp. (1935)
154. Keesom, W. H. and van Santen, J. J. M. The second virial coefficient of helium
Bull. inst. intern. froid, 7th Congr., 1st Comm. Inter., Rapports et Commun., 1-5 (1936)

155. Keesom, W. H. and Schweers, J. Measurements of the adsorption of helium on solidified layers of some gases
Physica 8, 1032-43 (1941)
156. Keesom, W. H. and Walstra, W. K. Isotherms of helium at liquid helium temperatures
Physica 6, 1146 (1939)
157. Keesom, W. H. and Walstra, W. K. The second virial coefficient of helium at temperatures of liquid and solid hydrogen
Physica 13, 225-30 (1947)
158. Keier, N. P. and Roginskii, S. Z. The kinetics of desorption of activated adsorbed hydrogen (in Russian)
Zhur. Fiz. Khim. 23, 897-916 (1949)
159. Keier, N. P. and Roginskii, S. Z. The properties of broadly heterogeneous surfaces as shown by the study of the adsorption of oxygen and hydrogen on activated charcoal (in Russian)
Problemy Kinetiki i Kalaliza, Akad. Nauk S.S.S.R. No. 7, 410-35 (1949)
160. Keller, W. E. Second virial coefficients of helium-3 -- helium-4 mixtures between 2° and 4° K
Phys. Rev. 100, 1021-2 (1955)
161. Kharakhorin, F. F. The phase relations in systems of liquefied gases. I. The binary mixture nitrogen-helium
Foreign Petrol. Technol. 9, 397-410 (1941)
162. Kihara, T. Virial coefficients and intermolecular potential of small, non-spherical molecules
J. Phys. Soc. Japan 11, 362-6 (1956)
163. Kilpatrick, J. E., Keller, W. E. and Hammel, E. F. Second virial coefficients of helium from the exp-six potential
Phys. Rev. 97, 9-12 (1955)
164. Kilpatrick, J. E., Keller, W. E., Hammel, E. F. and Metropolis, N. Second virial coefficients of helium³ and helium⁴
Phys. Rev. 94, 1103-10 (1954)

165. Kingman, F. E. T. Adsorption of hydrogen on charcoal
Nature 127, 742 (1931)
166. Kingman, F. E. T. Adsorption of hydrogen by charcoal
Trans. Faraday Soc. 28, 269-72 (1932)
167. Kinoshita, M. and Oisi, J. Expansion and pressure coefficients of nitrogen, hydrogen, helium and neon and the absolute temperature of 0°C
Phil. Mag. [7], 24, 52-62 (1937)
168. Kirkwood, J. G. and Keyes, F. G. The equation of state of helium
Phys. Rev. 37, 832-40 (1931)
169. Koeppe, W. The integral J-T effect for hydrogen at low temperatures and pressures up to 120 atmospheres (in German)
Kältetechnik 8, 275 (1956)
170. Kogan, V. S., Lazarev, B. G. and Bulatova, R. B. State diagram of the hydrogen-deuterium system (in Russian)
Zhur. Eksptl. i Teoret. Fiz. 34, 238-40 (1958)
171. Kolsky, R. G., Gilmer, R. M. and Gilles, P. W. Free-energy functions for 54 gaseous elements
J. Chem. Phys. 27, 494-5 (1957)
172. Kramer, G. M. and Miller, J. G. Compressibility of gases. III. The second and third virial coefficients of mixtures of helium and nitrogen at 30°C
J. Phys. Chem. 61, 785-8 (1957)
173. van Laar, J. J. The critical density of hydrogen, helium and neon (in Dutch)
Chem. Weekblad 16, 1557-64 (1919)
174. Lachowicz, S. K. The relative solubility of hydrogen and deuterium in liquids at low temperatures
Research Correspondence 8, No. 6, S 27-8 (1955)
175. Lang, R. J. The purification of helium
Trans. Roy. Soc. Can., Sect. III, 17, 181-8 (1923)

176. Laquer, H. L. Handling liquid hydrogen on a pilot plant scale
Advances in Cryogenic Eng. 5, 85-94 (1960)
177. Lennard-Jones, J. E. The molecule fields of hydrogen,
nitrogen and neon
Proc. Roy. Soc. (London) A112, 214-29 (1926)
178. Lenoir, J. M. and Hipkin, H. G. Equilibrium ratios of
hydrogen and the critical locus of hydrogen-paraffin mixtures
A.I.Ch.E. Journal 3, 318-20 (1957)
179. Livingston, M. K. The cross-sectional areas of molecules
adsorbed on solid surfaces
J. Colloid Sci. 4, 447-58 (1949)
180. Maidanovskaya, L. G. Adsorption of hydrogen on silica gel
and glass (in Russian)
Zhur. Fiz. Khim. 6, 1111-6 (1935)
181. Maidanovskaya, L. G., Panfilov, I. A. and Zakharova, R. O.
Adsorption of hydrogen and some electrolytes on iron oxide
(in Russian)
Uchenye Zapiski Tomsk. Gosudarst. Univ. im. V. V.
Kuibysheva, No. 26, 93-102 (1955)
182. Mann, D. B., Birmingham, B. W. and Vander Arend, P. C.
Technical aspects of large scale liquid helium liquefaction and
transportation
Advances in Cryogenic Eng. 3, 125-35 (1960)
183. Mann, D. B., Bjorklund, W. R., Macinko, J. and Hiza,
M. J. Design, construction and performance of a laboratory-
size helium liquefier
Advances in Cryogenic Eng. 5, 346-53 (1960)
184. Marshak, R. E., Morse, P. M. and York, H. Equation of
state of hydrogen, helium and Russell mixtures at high
temperatures and pressures
Astrophys. J. 111, 214-20 (1950)
185. Maslan, F. D. and Littman, T. M. Compressibility chart
for hydrogen and inert gases
Ind. Eng. Chem. 45, 1566-8 (1953)

186. Mastrangelo, S. V. R. and Aston, J. G. Thermodynamic data and some notes on the nature of absorbed helium
J. Chem. Phys. 19, 1370-5 (1951)
187. Mathias, E. and Crommelin, C. A. Carbon monoxide and helium (in French)
Ann. phys. 5, 137-66 (1936)
188. McBain, J. W. The mechanism of the adsorption of hydrogen by carbon
Phil. Mag [6], 18, 916-35 (1909)
189. McLean, S. The adsorption of helium by charcoal
Trans. Roy. Soc. Can., Sect. III, 12, 79-81 (1918)
190. Megaw, H. D. The density and compressibility of solid hydrogen and deuterium at 4.2°K
Phil. Mag. [7], 28, 129-47 (1939)
191. Michels, A., de Graaff, W., Wassenaar, T., Levelt, J. M. H. and Louwerse, P. Compressibility isotherms of hydrogen and deuterium at temperatures between -175°C and 150°C
Physica 25, 25-42 (1959)
192. Michels, A. and Gerver, A. J. J. A recalculation of the isothermal measurements for hydrogen of Kohnstamm and Walstra (in German)
Ann. Physik [5], 16, 745-50 (1933)
193. Michels, A. and Goudekot, M. Compressibility of hydrogen between 0° and 150° up to 3000 atmospheres
Physica 8, 353-9 (1941)
194. Michels, A. and Goudekot, M. Thermodynamic properties of hydrogen and deuterium up to 700 amagats between 0° and 150°
Physica 8, 387-97 (1941)
195. Michels, A., Nijhoff, G. P. and Gerver, A. J. J. Isothermal measurements on hydrogen between 0° and 100° and up to 1000 atmospheres (in German)
Ann. Physik [5], 12, 562-8 (1932)

196. Mills, R. L. and Grilly, E. R. Melting curves of helium³, helium⁴, hydrogen, deuterium, neon, nitrogen and oxygen up to 3500 kg/sq cm
Phys. Rev. 99, 480-6 (1955)
197. Mills, R. L. and Grilly, E. R. Melting curves of hydrogen, deuterium and tritium up to 3500 kg/sq cm
Phys. Rev. 101, 1246-7 (1956)
198. Miyako, R. Viscosity and second virial coefficients of gaseous hydrogen at low temperatures (in Japanese)
Proc. Phys. Math. Soc. Japan [3], 24, 852-63 (1942)
199. Mizushima, M. Theory of intermolecular potential and second virial coefficient of hydrogen at low temperatures
J. Chem. Phys. 21, 2107-14 (1953)
200. Moore, R. B. Helium: history, properties and commercial development. The uses of charcoal in helium purification
J. Franklin Inst. 191, 183-4 (1921)
201. Moore, R. W., Fowle, A. A., Bailey, B. M., Ruccia, F. E. and Reid, R. C. Gas-pressurized transfer of liquid hydrogen
Advances in Cryogenic Eng. 5, 450-9 (1960)
202. Mulders, E. M. J. and Scheffer, F. E. C. Analysis of mixtures of hydrogen, methane and ethane
Rec. trav. chim. 49, 1057-65 (1930)
203. Nelson, E. E. and Bonnell, W. S. Solubility of hydrogen in butane
Ind. Eng. Chem. 35, 204-6 (1943)
204. Neven, P. and van Tiggelen, A. Quantitative adsorption of hydrogen
Bull. soc. chim. Belges 61, 328-9 (1952)
205. Nijhoff, G. P. The second virial coefficient of helium and hydrogen
Commun. Kamerlingh Onnes Lab. Univ. Leiden, Suppl. No. 64, 17-27 (1929)

206. Nijhoff, G. P. and Keesom, W. H. Isotherms of hydrogen at temperatures from -225.5° to -248.3°C and pressures from 1.6 to 4.2 atmospheres
Commun. Kamerlingh Onnes Lab. Univ. Leiden No. 188e, 2pp. (1928)
207. Nijhoff, G. P. and Keesom, W. H. Isotherms of hydrogen at temperatures of 0° and 100°C
Commun. Kamerlingh Onnes Lab. Univ. Leiden No. 188d, 4pp. (1927)
208. Northcott, R. P. and Porter, H. T. Hydrogen from petroleum and its uses
Brit. Chem. Eng. 3, 542-5; 614-7 (1958)
209. Oiski, J. 0° and 100° isotherms of helium, hydrogen, neon, argon, air and carbon dioxide at pressures below 2 atmospheres and absolute temperature, 0°C
J. Sci. Research Inst. (Tokyo) 43, 220-31 (1949)
210. Ordin, P. M., Weiss, S. and Christenson, H. Pressure-temperature histories of liquid hydrogen under pressurization and venting conditions
Advances in Cryogenic Eng. 5, 481-6 (1960)
211. Paal, C. and Hartman, W. Gaseometric determination of hydrogen by catalytic absorption (in German)
Ber. 43, 243-58 (1910)
212. Palazzo, D. F., Schreiner, W. C. and Skaperdas, G. T. Low temperature recovery of hydrogen from refinery gases
Ind. Eng. Chem. 49, 685-8 (1957)
213. Paneth, F. and Peters, K. Helium studies. I. Method for the detection of small quantities of helium (in German)
Z. physik. Chem. 134, 353-73 (1928)
214. Perkins, W. E. and Frainier, R. J. Practical storage and distribution of liquid hydrogen and helium
Advances in Cryogenic Eng. 5, 69-76 (1960)
215. Peshkov, V. P., Zinoveva, K. N. and Filimonov, A. I. Helium-3 cryostats (in Russian)
Zhur. Eksptl. i Teoret. Fiz. 36, 1034-7 (1959)

216. Peter, S. and Weinert, M. Solubility of hydrogen, carbon monoxide, carbon dioxide and water vapor in liquid hydrocarbons (in German)
Z. physik. Chem. (Frankfurt) [N.F.] 5, 114-21 (1955)
217. Petit, P. Solubility of nitrogen in hydrogen below the critical temperature of nitrogen (in French)
Compt. rend. 246, 1171-2 (1957)
218. Phillips, T. D. Adsorption of hydrogen
Phys. Rev. 45, 215 (1934)
219. Pietrusky, K. Helium
Chemiker - Ztg. 61, 661-2 (1937)
220. Podgurski, H. H. and Emmett, P. H. The adsorption of hydrogen and carbon monoxide on iron surfaces
J. Phys. Chem. 57, 159-64 (1953)
221. Pollard, F. H. The adsorption of carbon monoxide and hydrogen by platinized asbestos
J. Phys. Chem. 27, 356-75 (1923)
222. Pope, D. H., Killina, W. R. and Corbett, R. J. Single-phase flow tests with liquid hydrogen
Advances in Cryogenic Eng. 5, 441-9 (1960)
223. Powers, R. W., Mattox, R. W. and Johnston, H. L. Thermal conductivity of liquid normal and para-hydrogen from 15° to 27°K
J. Am. Chem. Soc. 76, 5972-3 (1954)
224. Prausnitz, J. M. and Benson, P. R. Solubility of liquids in compressed hydrogen, nitrogen and carbon dioxide
A.I.Ch.E. Journal 5, 161-4 (1959)
225. Reid, R. C. and Sherwood, T. K. The properties of gases and liquids
McGraw-Hill Book Co., New York, 386pp. (1958)
226. Reyerson, L. H. The adsorption of hydrogen by silica gel at elevated temperatures
J. Am. Chem. Soc. 55, 3105-8 (1933)

227. Richards, R. J., Robbins, R. F., Jacobs, R. B. and Holten, D. C. Heat transfer to boiling liquid nitrogen and hydrogen flowing axially through narrow annular passages *Advances in Cryogenic Eng.* 3, 375-89 (1960)
228. Richards, R. J., Steward, W. G. and Jacobs, R. B. Transfer of liquid hydrogen uninsulated lines *Advances in Cryogenic Eng.* 5, 103-10 (1960)
229. Rinderer, L. and Haenssler, F. Heat transfer to helium II for big differences of temperature between heated wall and super-fluid helium bath *Advances in Cryogenic Eng.* 5, 225 (1960)
230. Rogers, J. D. Two-phase flow of hydrogen in horizontal tubes *A.I.Ch.E. Journal* 2, 536-8 (1956)
231. Rudenko, N. S. Molecular weight, density and viscosity of liquefied gases (in Russian) *Zhur. Tekh. Fiz.* 18, 1123-6 (1948)
232. Ruhemann, M. and Fedoritenko, A. The use of the I-X diagram (heat content vs. composition) in the separation of helium and nitrogen (in Russian) *Zhur. Khim. Prom.* 14, 28-31 (1937)
233. Satterly, J. Physical properties of solid and liquid helium *Rev. Modern Phys.* 8, 347-57 (1936)
234. Sattler, H. Solubility of hydrogen in liquid hydrocarbons (in German) *Z. tech. Physik* 21, 410-3 (1940)
235. Schaefer, C. A. and Thodos, G. Reduced density correlation for hydrogen; liquid and gaseous states *A.I.Ch.E. Journal* 5, 155-8 (1959)
236. Schaefer, C. A. and Thodos, G. Reduced thermal conductivity correlation. Gaseous and liquid hydrogen *Ind. Eng. Chem.* 50, 1585-8 (1958)
237. Schaeffer, W. D., Smith, W. R. and Wendell, C. B. The adsorption of helium on carbon black at liquid helium temperatures *J. Am. Chem. Soc.* 71, 863-7 (1949)

238. Schafer, K. The second virial coefficient of the different modifications of light and heavy hydrogen. I. Experimental determination (in German)
Z. physik. Chem. B36, 85-104 (1937)
239. Schafer, K. The second virial coefficient of the different modifications of light and heavy hydrogen. II. Theoretical calculations (in German)
Z. physik. Chem. B38, 187-208 (1937)
240. Schames, L. Direct relationship of equation of state and internal friction of nitrogen, helium, neon, hydrogen, air, argon and oxygen (in German)
Physik. Z. 32, 16-20 (1931)
241. Scott, G. A. Isotherms of hydrogen, carbon monoxide and their mixtures
Proc. Roy. Soc. (London) A125, 330-44 (1929)
242. Scott, R. B. and Brickwedde, F. G. Molecular volumes and expansivities of liquid normal hydrogen and parahydrogen
J. Chem. Phys. 5, 5, 736-44 (1937)
243. Scott, R. B., Brickwedde, F. G., Urey, H. C. and Wahl, M. H. The vapor pressures and derived thermal properties of hydrogen and deuterium
J. Chem. Phys. 2, 454-64 (1934)
244. Sellers, E. S. and Augood, D. R. The distillation characteristics of liquid hydrogen
Trans. Inst. Chem. Engrs. (London) 34, 53-78 (1956)
245. Simon, F., Ruhemann, M. and Edwards, W. A. M. Melting point curves of hydrogen, neon, nitrogen and argon (in German)
Z. physik. Chem. B6, 331-42 (1929)
246. Smith, A. L., Hallett, N. C. and Johnston, H. L. Condensed gas calorimetry. VI. The heat capacity of liquid para-hydrogen from the boiling point to the critical point
J. Am. Chem. Soc. 76, 1486-8 (1954)

247. Smith, S. R. I. Gas-liquid phase equilibria in the system helium-hydrogen. II. Development of mass spectrometer techniques for analysis of helium-hydrogen and their isotopes Ph.D. Thesis, Ohio State Univ., Columbus (1952)
248. Stewart, R. B. and Johnson, V. J. A compilation and correlation of the p-v-t data of normal hydrogen from saturated liquid to 80°K
Advances in Cryogenic Eng. 5, 557-65 (1960)
249. Storfer, E. Heterogeneous catalysis. I. Activated adsorption of hydrogen on charcoal (in German)
Z. Elektrochem. 41, 198-204 (1935)
250. Swim, R. T. Temperature distribution in liquid and vapor phases of helium in cylindrical dewars
Advances in Cryogenic Eng. 5, 498-504 (1960)
251. Timmerhaus, K. D., Weitzel, D. H. and Flynn, T. M. Low-temperature distillation of hydrogen isotopes
Chem. Eng. Progr. 54, No. 6, 35-46 (1958)
252. Townend, D. T. A. and Bhatt, L. A. Isotherms of hydrogen, carbon monoxide and their mixture
Proc. Roy. Soc. (London) A134, 502-12 (1931)
253. Tsiklis, D. S. Limited mutual solubilities of gases at high pressures in the helium-propane system (in Russian)
Doklady Akad. Nauk S.S.S.R. 101, 129-30 (1955)
254. Tsiklis, D. S. Limited mutual solubility of gases under high pressure in the systems helium-ammonia and helium-carbon dioxide (in Russian)
Doklady Akad. Nauk S.S.S.R. 86, 1159-61 (1952)
255. Ubbelohde, A. R. Kinetics of adsorption processes. III. Influence of nuclear spin on sorption of hydrogen on charcoal
Trans. Faraday Soc. 28, 291-9 (1932)
256. Vander Arend, P. C. Large-scale production, handling and storage of liquid hydrogen
Advances in Cryogenic Eng. 5, 49-54 (1960)

257. Van Der Waarden, M. and Scheffer, F. E. C. Adsorption of nitrogen, hydrogen and their mixtures on silica gel
Rec. trav. chim 71, 689-98 (1952)
258. Verschoye, T. T. H. Isotherms of hydrogen, nitrogen and hydrogen-nitrogen mixtures at 0° and 20° up to a pressure of 200 atmospheres
Proc. Roy. Soc. (London) A111, 552-76 (1926)
259. von Glahn, U. H. and Lewis, J. P. Nucleate and film boiling studies with liquid hydrogen
Advances in Cryogenic Eng. 5, 262-72 (1960)
260. Wheeler, H. P., Jr. and Swenarton, L. B. Helium. Bibliography of technical and scientific literature from its discovery (1868) to Jan. 1, 1947
U. S. Bur. Mines, Bull. No. 484, 76pp. (1952)
261. White, D., Friedman, A. S. and Johnston, H. L. Direct determination of the critical temperature and critical pressure of normal hydrogen
J. Am. Chem. Soc. 72, 3565-70 (1950)
262. White, D., Friedman, A. S. and Johnston, H. L. The vapor pressure of normal hydrogen from the boiling point to the critical point
J. Am. Chem. Soc. 72, 3927-30 (1950)
263. Wiebe, R. and Gaddy, V. L. The compressibilities of hydrogen and four mixtures of hydrogen and nitrogen at 0°, 25°, 50°, 100°, 200° and 300° and to 1000 atmospheres
J. Am. Chem. Soc. 60, 2300-3 (1938)
264. Wiebe, R., Gaddy, V. L. and Heins, C., Jr. Compressibility isotherms of helium at temperatures from -70° to 200° and at pressures to 1000 atmospheres
J. Am. Chem. Soc. 53, 1721-5 (1931)
265. Woolley, H. W., Scott, R. B. and Brickwedde, F. G. Compilation of thermal properties of hydrogen in its various isotopic and ortho-para modifications
J. Research Natl. Bur. Standards 41, 379-475 (1948)

266. Woolsey, G. Critical constants of the inert gases and of hydrogen compounds having the same number of electrons per molecule
J. Am. Chem. Soc. 59, 1577-8 (1937)
267. Wright, C. C. Design, construction and testing of a helium-to-hydrogen heat exchanger
Advances in Cryogenic Eng. 5, 244-53 (1960)
268. Yushkevich, N. F. and Zhavoronkov, N. M. The purification of hydrogen and hydrogen-nitrogen mixtures from carbon monoxide in the synthetic ammonia industry (in Russian)
Zhur. Khim. Prom. 11, 18-24 (1934)
269. Zielinski, E. Separation of helium-neon-nitrogen mixtures by a combination adsorption and desorption method (in Polish)
Przemysl Chem. 13, 642-6 (1957)
270. Zinoveva, K. N. Determination of small amounts of admixed nitrogen and oxygen in hydrogen and helium (in Russian)
Zavodskaya Lab. 21, 30-2 (1955)
271. Zlunitsyn, S. A. and Rudenko, N. S. Compressibility of hydrogen at low temperatures (in Russian)
Zhur. Eksptl. i Teoret. Fiz. 16, 776-9 (1946)

9.0

Appendix

TABLE I

HELIUM-HYDROGEN
PRESSURE-CONCENTRATION DATA

Reference: Smith (247)

Temperature °K	Pressure atm	Liquid		Vapor		K	
		Mole % He	Mole % H ₂	Mole % He	Mole % H ₂	He	H ₂
17.4	3.27	0.19	99.81	83.40	16.60	439	0.166
17.4	3.27	0.20	99.80	83.50	16.50	418	0.165
17.4	5.65	0.22	99.78	90.10	9.90	410	0.0992
17.4	5.65	0.28	99.72	90.80	9.20	324	0.0923
17.4	6.53	0.27	99.73	91.76	8.24	340	0.0826
17.4	9.59	0.45	99.55	93.47	6.53	208	0.0656
17.4	9.59	0.51	99.49	93.41	6.59	183	0.0662
17.4	14.08	0.67	99.33	94.31	5.69	141	0.0573
17.4	14.08	0.74	99.26	94.44	5.56	128	0.0560
17.4	21.50	1.05	98.95	95.04	4.96	90.5	0.0501
17.4	21.50	1.08	98.92	95.02	4.98	88.0	0.0503
17.4	24.35	1.11	98.89	95.16	4.84	85.7	0.0489
17.4	24.35	1.15	98.85	95.21	4.79	82.8	0.0485
20.4	4.29	0.59	99.41	72.90	27.10	124	0.273
20.4	6.94	0.87	99.13	82.50	17.50	94.8	0.177
20.4	12.04	1.53	98.47	87.20	12.80	56.9	0.130
20.4	17.41	2.16	97.84	89.00	11.00	41.2	0.112
20.4	19.80	2.47	97.53	90.16	9.84	36.5	0.101
20.4	23.81	2.77	97.23	90.70	9.30	32.7	0.0956
20.4	24.83	2.95	97.05	90.20	9.80	30.6	0.101
20.4	24.83	2.97	97.03	90.20	9.80	30.4	0.101
20.4	25.51	2.89	97.11	90.70	9.30	31.4	0.0958
20.4	27.62	3.06	96.94	90.40	9.60	29.5	0.0990
21.8	2.93	0.18	99.82	61.3 *	38.7 *	341	0.388
21.8	3.74	0.34*	99.66*	65.8	34.2	194	0.343
21.8	5.17	0.52*	99.48*	71.5	28.5	138	0.286
21.8	5.58	0.29	99.71	74.0 *	26.0 *	255	0.261
21.8	10.68	1.21	98.79	83.6	16.4	69.1	0.166
21.8	10.68	1.36	98.64	83.7	16.3	61.5	0.165
21.8	12.86	1.55*	98.45*	82.2	17.8	53.0	0.181
21.8	20.82	2.44	97.56	88.9 *	11.1 *	36.4	0.114
21.8	26.26	3.06	96.94	87.4	12.6	28.6	0.130
21.8	26.26	3.13	96.87	87.2	12.8	27.9	0.132
21.8	30.41	3.38*	96.62*	88.9	11.1	26.3	0.115

NOTE: * Values taken from Smith's Figures



THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its major laboratories in Washington, D.C., and Boulder, Colorado, is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by the title. A brief description of the activities, and of the resultant publications, appears on the inside of the front cover.

WASHINGTON, D.C.

Electricity. Resistance and Reactance. Electrochemistry. Electrical Instruments. Magnetic Measurements. Dielectrics.

Metrology. Photometry and Colorimetry. Refractometry. Photographic Research. Length. Engineering Metrology. Mass and Scale. Volumetry and Densimetry.

Heat. Temperature Physics. Heat Measurements. Cryogenic Physics. Equation of State. Statistical Physics. **Radiation Physics.** X-ray. Radioactivity. Radiation Theory. High Energy Radiation. Radiological Equipment. **Nucleonic Instrumentation.** Neutron Physics.

Analytical and Inorganic Chemistry. Pure Substances. Spectrochemistry. Solution Chemistry. Standard Reference Materials. Applied Analytical Research.

Mechanics. Sound. Pressure and Vacuum. Fluid Mechanics. Engineering Mechanics. Rheology. Combustion Controls.

Organic and Fibrous Materials. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

Metallurgy. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics. Electrolysis and Metal Deposition.

Mineral Products. Engineering Ceramics. Glass. Refractories. Enameled Metals. Crystal Growth. Physical Properties. Constitution and Microstructure.

Building Research. Structural Engineering. Fire Research. Mechanical Systems. Organic Building Materials. Codes and Safety Standards. Heat Transfer. Inorganic Building Materials.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics. Operations Research.

Data Processing Systems. Components and Techniques. Digital Circuitry. Digital Systems. Analog Systems. Applications Engineering.

Atomic Physics. Spectroscopy. Infrared Spectroscopy. Solid State Physics. Electron Physics. Atomic Physics. **Instrumentation.** Engineering Electronics. Electron Devices. Electronic Instrumentation. Mechanical Instruments. Basic Instrumentation.

Physical Chemistry. Thermochemistry. Surface Chemistry. Organic Chemistry. Molecular Spectroscopy. Molecular Kinetics. Mass Spectrometry.

Office of Weights and Measures.

BOULDER, COLO.

Cryogenic Engineering. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Cryogenic Technical Services.

Ionosphere Research and Propagation. Low Frequency and Very Low Frequency Research. Ionosphere Research. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services.

Radio Propagation Engineering. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation-Terrain Effects. Radio-Meteorology. Lower Atmosphere Physics.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. Radio and Microwave Materials. Atomic Frequency and Time Interval Standards. Electronic Calibration Center. Millimeter-Wave Research. Microwave Circuit Standards.

Radio Systems. High Frequency and Very High Frequency Research. Modulation Research. Antenna Research. Navigation Systems.

Upper Atmosphere and Space Physics. Upper Atmosphere and Plasma Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

